

CEMENT AND LIME MANUFACTURE

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The Thermal Efficiency of the Rotary Cement Kiln.

By HANS GYGI.
(ZURICH.)

I.—Introduction.

DURING recent years many endeavours have been made to improve the efficiency of the rotary kiln used for burning Portland cement clinker and to increase the size of the unit. In these attempts the various firms have by no means followed the same lines in kiln design.

The reason for the adoption of such radically different forms of construction is that no thorough investigation has been made of the processes that take place in the kiln and, in consequence, there is no information about the manner in which heat is transferred from the combustion gases to the material to be burned. Until the phenomena of heat transfer in the cement kiln are completely understood, it will not be possible to establish any criterion for its dimensions without the risk of serious errors in our views as to the most favourable form of kiln.

The author has undertaken an experimental investigation with the object of adding to our knowledge of the processes involved in the burning of cement in the rotary kiln. It was found possible, by means of a carefully calculated heat balance in conjunction with numerous measurements of the temperatures inside the kiln, simultaneous sampling, and an investigation of the processes of combustion, to make an experimental determination of the heat transfer per metre length of kiln. An exact theoretical analysis of the heat transfer at three cross-sections of the kiln was then attempted. Although the attempt quantitatively to determine the heat transfer in the drying zone was unsuccessful it was found possible to calculate heat transfer in the pre-heating zone and the burning zone. The accuracy of these calculations must not be over-estimated, but nevertheless they are of great importance because they show clearly what are the

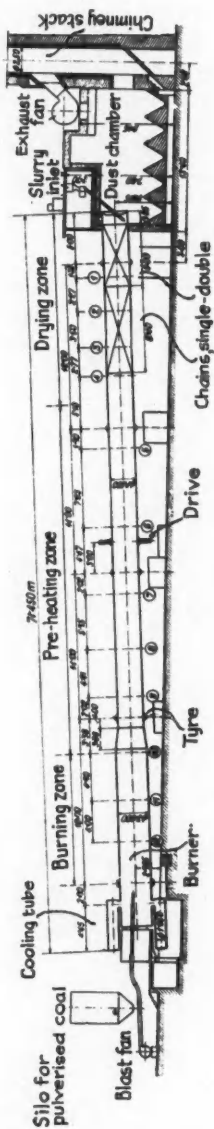


Fig. 1.—Vertical section of the kiln investigated showing position of the cross-sections (1)—(12) at which the measurements were made.

laws governing heat transfer in the cement kiln and what factors are of significance.

The experiments upon which this study is based were carried out on a rotary kiln operating by the wet process. Its construction is shown in *Fig. 1*. The external diameter of the steel tube is 3,000 mm. at the burning zone and 2,500 mm. at the pre-heating zone. The kiln is 69,000 mm. long, its inclination is 5 per cent., and normally it rotates once in 78 seconds. The drying zone is furnished with chains to increase heat transfer by convection. A tubular cooler consisting of twelve cooling tubes each 4,450 mm. long and 1,050 mm. in diameter cools the clinker and pre-heats the secondary air. The slurry is fed in constant quantities through an inclined tube by means of a slurry lifter. The kiln is fired with pulverised coal by a simple arrangement in which the unwarmed primary air is used to carry the fuel so that the primary air and the pulverised coal are not mixed with the secondary air until they have emerged from the burner, which is an ordinary pipe.

II.—THE HEAT BALANCE.

(1) The Theoretical Heat Balance for the Production of 1 kg. of Clinker.

The heat consumption of the kiln is made up of the heat theoretically required for the process and the heat dissipated or lost. When drawing up a heat balance we are only able to measure heat input and heat losses, and for this reason we shall first calculate the heat effects which correspond to the theoretical heat requirement for the production of 1 kg. of clinker.

Under heat effects is to be understood the amount of heat which, assuming the burning process to be carried out without heat losses, would be required to produce from raw materials having an initial temperature of 0 deg. C. cement clinker with a final temperature of 0 deg. C. The heat consumption therefore comprises the three endothermic processes, namely, dehydration of the clay content of the raw material, decarbonation of the lime, and clinker formation. To be deducted from this heat consumption are the quantity of heat evolved during the formation of certain clinker minerals and the heat contents of the carbon dioxide liberated by the dissociation of the carbonates and of the water vapour driven off from the clay. It must be borne in mind, however, that the heat consumed in heating the raw material up to the reaction temperature and the heat recovered in cooling the clinker from sintering temperature to 0 deg. C. cannot balance, because a complete change has been brought about in the state of the material.

In order to be able to draw up a theoretical heat balance for the production of the clinker, we must know the specific heats of the pure components of the raw materials; these have been determined for the temperature range concerned by Schwiete and Elsner v. Gronow.¹ Further, we must know the specific heat of the clinker; this has also been determined by Schwiete.² Having calculated the amount of heat consumed in heating the raw material and the amount

¹ Schwiete und Elsner v. Gronow, "Zement," No. 13 (1935).

² Eitel und Schwiete, "Zement," No. 25 (1932).

recovered from the cooling clinker, we come to the determination of the first heat effect at 450 deg. C., the decomposition temperature of the kaolin. Klever and Kordes found this to be 145 Kcal. per kg. kaolin at 20 deg. C. Elsner v. Gronow³ has shown, however, by means of a cyclic process and Hess's law, that for the technically significant temperature of 450 deg. C. the heat required for the dehydration of kaolin is 223 Kcal. per kg.

The next stage is the decarbonation of the limestone, a markedly endothermic reaction which occurs at about 900 deg. C. This heat effect has been known for some time and amounts to 425 Kcal. per kg. limestone at 20 deg. C. In the absence of direct determinations at the technically important temperature of 900 deg. C., this value was used until recently as a basis for calculation. Elsner v. Gronow and Schwiete⁴ have shown, however, that the heat of dissociation of limestone at 900 deg. C. is only 396 Kcal. per kg. of calcium carbonate.

In view of the importance of the endothermic effect associated with the decarbonation of limestone, it may be of interest to show how this calculation is carried out. The mean specific heats of CaO, CaCO₃ and CO₂ for the temperature range 20 deg. C. to 900 deg. C. are

$$\begin{aligned} c_{\text{CaO}} &= 0.213 \\ c_{\text{CaCO}_3} &= 0.266 \\ c_{\text{CO}_2} &= 0.255 \end{aligned}$$

The cycle upon which the calculation of the heat effect at 900 deg. C. is based comprises the following five steps:

- (1) 1 kg. CaCO₃ is heated from 20 deg. C. to 900 deg. C.
The heat consumption is - 235 Kcal.
- (2) 1 kg. CaCO₃ dissociates at 900 deg. C. giving 0.560 kg. CaO and 0.440 kg. CO₂. The value of this heat effect is - x Kcal.
- (3) 0.560 kg. CaO is cooled from 900 deg. C. to 20 deg. C.
The heat recovered is + 105 Kcal.
- (4) 0.440 kg. CO₂ is cooled from 900 deg. C. to 20 deg. C.
The heat recovered is + 99 Kcal.
- (5) The heat of formation of 1 kg. of CaO + CO₂ = CaCO₃ at 20 deg. C. is + 425 Kcal.

According to Hess's law the sum of all the heat effects must equal zero, and therefore

$$x = -235 + 105 + 99 + 425 = 396 \text{ Kcal. per kg. CaCO}_3.$$

The heat required for clinker formation at temperatures above 1,200 deg. C. was first introduced into the calculation by Elsner v. Gronow,³ who assumed the value of 22 Kcal. per kg. of clinker, which corresponds to the value for the greater energy content of the clinker as compared with crystalline tricalcium silicate measured by Schwiete at 1,400 deg. C.

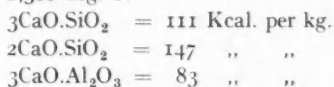
³ Elsner v. Gronow, "Zement," Nos. 26 and 27 (1936).

⁴ Elsner v. Gronow and Schwiete, "Zement," No. 18 (1935).

Following these remarks on the specific heats of the raw materials and the clinker and the endothermic reactions, it should be mentioned that crystallisation of the alumina from the clay content occurs at about 950 deg. C. and liberates 72 Kcal. per kg. of metakaolin.

It will be seen from Fig. 8* that the raw material in the vicinity of cross-section No. 11 has a temperature of 950 deg. C., and Table 7* gives the insoluble content of the sample of material taken at this cross-section as 4.29 per cent. The analysis of the insoluble portion of the sample gave a silica content of 77.06 per cent., while only 4.09 per cent. of alumina was present. This shows that at 950 deg. C. 3.22 per cent. of the alumina content of the raw material is in the free state, so that when the heat balance is drawn up the exothermic effect associated with the crystallisation of the amorphous constituents of the metakaolin is negligible.

Great attention must now be given to the exothermic effects connected with the formation of the clinker minerals. Values for these have been determined experimentally by Elsner v. Gronow and Schwiete⁵ at 20 deg. C. From these results the following values were calculated for the heat effects of the various clinker components at 1,300 deg. C.



The clinker for which it is proposed to calculate the heat effects has the following chemical composition :

	per cent.
Insoluble	= 0.17
SiO ₂	= 20.88
Al ₂ O ₃	= 6.02
Fe ₂ O ₃	= 3.58
CaO (combined)	= 66.13
CaO (free)	= 0.20
MgO	= 2.08
SO ₃	= 0.30
K ₂ O + Na ₂ O	= 0.63
	<hr/>
	99.99

If we know the chemical composition and the minerals of which the clinker is composed the proportion of the various cement compounds can be calculated. Research has shown that Portland cement clinker consists mainly of 3CaO.SiO₂, 2CaO.SiO₂, 3CaO.Al₂O₃, 4CaO.Al₂O₃.Fe₂O₃, MgO, and some free lime. In addition there are small quantities of K₂O and Na₂O, but we do not know in what compounds these oxides are present. According to Bogue,⁶ the clinker under consideration will have the compound composition given in the first column of Table 1. The direct calculation of the compound composition from the chemical analysis can, however, only give approximate values because Bogue

* Fig. 8 and Table 7 will be given in the next instalment of this paper.

⁵ Elsner v. Gronow and Schwiete, "Zement," No. 35 (1935).

⁶ R. H. Bogue, "Ind. and Eng. Chemistry," page 192 (1929).

assumed that Portland cement clinker is made up entirely of crystalline components. This is not correct, for most clinkers contain a certain amount of glassy material. Lea⁷ has given a method for calculating the compound composition of clinker on the assumption that the equilibrium at the sintering temperature is frozen.

The values in the second column of Table I show the compound composition of the clinker if it is assumed that the liquid phase crystallises independently, while in the third column are given the values calculated on the assumption that the liquid phase forms a glass. It is, however, impossible to say to what extent the liquid phase crystallises or forms a glass in reality. Furthermore, according to Lea, the effects of the magnesia and the alkalis on equilibrium conditions are still unknown. Moreover, in the calculation of the heat effects we cannot

TABLE I.—EFFECT OF COOLING CONDITIONS ON THE FORMATION OF CEMENT COMPOUNDS.

Cement compounds.	Crystalline constituents only. R. H. Bogue.	Liquid phase crystallises independently. F. M. Lea.	Liquid phase forms a glass. F. M. Lea.
3 CaO SiO ₂	64.18	65.00	65.05
2 CaO SiO ₂	11.46	10.56	5.64
3 CaO Al ₂ O ₃	9.88	9.21	0
4 CaO Al ₂ O ₃ Fe ₂ O ₃	10.88	10.88	0
5 CaO 3 Al ₂ O ₃	0	0.77	0
Glass	0	0	25.65

include a value corresponding to the ferric oxide content of the raw materials because the heat of formation of 4CaO.Al₂O₃.Fe₂O₃ is not known. The ferric oxide content will therefore be added to the alumina and, further, it will be assumed that the clinker will contain no impurities whatsoever. This simplification seems permissible because the ferric oxide can be replaced by alumina and only a residue of 3.39 per cent. remains unaccounted for in the clinker.

On these assumptions we have the following chemical composition for the clinker under consideration :

SiO ₂	=	21.62 per cent.
Al ₂ O ₃	=	9.93 "
CaO	=	68.45 "
		100.00 "

The clinker consists of crystalline components and has the following compound composition :

3CaO.SiO ₂	=	49.0 per cent.
2CaO.SiO ₂	=	24.7 "
3CaO.Al ₂ O ₃	=	26.3 "
		100.0 "

The raw material consists of calcium carbonate, kaolin, and silica in the form

⁷ F. M. Lea and C. H. Desch, "Chemistry of Cement and Concrete," 1935, page 119.

of quartz. The following quantities are therefore required for the production of 1 kg. of clinker:

$$\begin{aligned}\text{CaCO}_3 &= 1.221 \text{ kg.} \\ \text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O} &= 0.251 \text{ ,,} \\ \text{SiO}_2 &= 0.099 \text{ ,,} \\ &\underline{1.571 \text{ ,,}}\end{aligned}$$

We can now return to the theoretical heat balance, making use of all the factors discussed. In so doing we shall very largely follow the procedure first described by Eitel and Schwiete.²

HEAT CONSUMPTION—

- (1) Heating the raw materials from 0 deg. C. to 450 deg. C.,

$$\begin{aligned}1.221 \times 0.248 \times 450 &= 136.2 \text{ Kcal.} \\ 0.251 \times 0.280 \times 450 &= 31.6 \text{ ,,} \\ 0.099 \times 0.239 \times 450 &= 10.7 \text{ ,,} \\ &\underline{178.5} \text{ .. } 179 \text{ Kcal.}\end{aligned}$$
 - (2) Endothermic dehydration of the kaolin,

$$0.251 \times 223 = 55.9 \text{ Kcal.} \text{ .. } 56 \text{ Kcal.}$$
 - (3) Heating the raw materials with the kaolin dehydrated to 900 deg. C.,

$$\begin{aligned}1.221 (0.266 \times 900 - 0.248 \times 450) &= 155.0 \text{ Kcal.} \\ 0.216 (0.258 \times 900 - 0.238 \times 450) &= 27.0 \text{ ,,} \\ 0.099 (0.263 \times 900 - 0.239 \times 450) &= 12.8 \text{ ,,} \\ &\underline{194.8} \text{ .. } 195 \text{ Kcal.}\end{aligned}$$
 - (4) Endothermic decarbonation of the calcium carbonate,

$$1.211 \times 396 = 483 \text{ Kcal.} \text{ .. } 483 \text{ Kcal.}$$
 - (5) Heating the decarbonated raw materials from 900 deg. C. to the sintering temperature (1,400 deg. C.),

$$\begin{aligned}0.685 (0.218 \times 1,400 - 0.213 \times 900) &= 77.7 \text{ Kcal.} \\ 0.216 (0.270 \times 1,400 - 0.258 \times 900) &= 31.5 \text{ ,,} \\ 0.099 (0.271 \times 1,400 - 0.263 \times 900) &= 14.0 \text{ ,,} \\ &\underline{123.2} \text{ .. } 123 \text{ Kcal.}\end{aligned}$$
 - (6) Endothermic formation of liquid phase .. 22 Kcal.
- Sum of heat requirements and endothermic effects .. 1,058 Kcal.

HEAT GAINS—

- (1) Exothermic formation of cement compounds,

$$\begin{aligned}3\text{CaO} \cdot \text{SiO}_2 &= 0.490 \times 111 = 54.4 \text{ Kcal.} \\ 2\text{CaO} \cdot \text{SiO}_2 &= 0.247 \times 147 = 36.3 \text{ ,,} \\ 3\text{CaO} \cdot \text{Al}_2\text{O}_3 &= 0.263 \times 83 = 21.8 \text{ ,,} \\ &\underline{112.5} \text{ Kcal.} \text{ .. } 113 \text{ Kcal.}\end{aligned}$$
- (2) Cooling of the clinker,

$$1.00 \times 1,400 \times 0.261 = 366 \text{ Kcal.} \text{ .. } 366 \text{ Kcal.}$$
- (3) Cooling of the carbon dioxide driven off from the calcium carbonate,

$$0.537 \times 0.257 \times 900 = 124 \text{ Kcal.} \text{ .. } 124 \text{ Kcal.}$$
- (4) Cooling of the water vapour expelled from the kaolin,

$$0.035 \times 0.472 \times 450 = 7.43 \text{ Kcal.} \text{ .. } 7 \text{ Kcal.}$$

Sum of heat gains .. 610 Kcal.

HEAT EFFECT.—The difference between the heat consumption and the heat gain gives the heat effect for burning 1 kg. of Portland cement clinker as

$$\begin{aligned}448 \text{ Kcal. per kg.} \\ (\text{To be continued.})\end{aligned}$$

Research on Cement and Lime.

The following notes are from the annual report of the Building Research Station for the year 1936 (published by H.M. Stationery Office, price 4s. net). Much of the section dealing with cement has already been published in the form of technical papers.

The Constituent Compounds of Set Cements.

Calcium Sulpho-aluminates.—Progress has been made in the study of the solubility equilibria of the high sulphate form of calcium sulpho-aluminate in various solutions undertaken in connection with the attack on cement by sea water and salt solutions. With a solution of sodium chloride containing 30 grams of NaCl per litre, the equilibrium pH value at 25 deg. C. is 11.05, and the equilibrium solution contains 0.115 g. Al_2O_3 , 0.295 g. CaO, and 0.230 g. SO_3 per litre. Similarly, with a solution of sodium sulphate containing 50 g. Na_2SO_4 per litre, the equilibrium pH value at 25 deg. C. is 10.79, and the equilibrium solution contains 0.065 g. Al_2O_3 , and 0.185 g. CaO per litre. Values previously found for calcium sulpho-aluminate shaken with water only at 25 deg. C. are $pH = 10.80$, 0.035 g. Al_2O_3 , 0.130 g. CaO, 0.125 g. SO_3 per litre.

Hydrated Calcium Aluminates.—Since the year 1933 intermittent work only has been possible on the system lime-alumina-water, but sufficient data have now accumulated to enable the general phase relations at 25 deg. C. to be outlined. The stable phases over practically the whole solubility field are the tricalcium aluminate hexahydrate ($3CaO \cdot Al_2O_3 \cdot 6H_2O$) and hydrated alumina. A tetracalcium aluminate hydrate occurs as a stable phase over a small range of lime concentrations approaching that of saturated lime solutions. In addition there are two other tricalcium aluminate hydrates ($3CaO \cdot Al_2O_3 \cdot 12H_2O$ and $3CaO \cdot Al_2O_3 \cdot 18H_2O$) and a dicalcium aluminate hydrate, all of which are metastable in respect to the tricalcium aluminate hexahydrate. The rate of inversion of the metastable into the stable compounds increases markedly as the temperature is raised. Certain other compounds described by other workers have not been observed during this investigation. The solubilities and conditions of formation of the various metastable compounds are very similar, and a complete definition of their relative solubility curves has not been found possible. The results obtained, however, indicate the more important features of the system and the ultimate equilibrium in the hydration of the calcium aluminates in cements.

Hydrated Calcium Silicates.—The study of the crystalline compounds formed by exposure of the anhydrous calcium silicates to high pressure steam has been extended to the examination of the effect of treating silicate gels, and various mixtures of lime with silica gel, in the same manner. It has been found that gels of a lime-silica ratio of 1:1 form a crystalline compound with a composition corresponding to the formula $CaO \cdot SiO_2 \cdot \frac{1}{2}H_2O$. These crystalline products are being examined by X-ray analysis to determine whether they form a solid solution series or are mixtures of crystals of almost identical optical properties.

Fineness of Portland Cements.

The Wagner turbidimeter for the measurement of the surface area of cements has been calibrated and checked against a standard cement sample prepared by the National Bureau of Standards, Washington; satisfactory agreement was found.

Pozzolanas.

The work on pozzolanas is now almost entirely confined to the development of methods of test suitable for specification purposes. Investigations have been continued on the methods of test mentioned in the last report and comparative tests have also been made in the laboratories of two cement manufacturers. The results of these comparative tests indicate that a closer definition of the various test conditions is necessary.

Foamed Slag.

Tests have been carried out to determine whether foamed slag forms a stable aggregate, and in particular if it exhibits the "falling" phenomenon associated with air-cooled slags of high lime content. The results of this examination are satisfactory and it is concluded that the foaming process stabilises slags which would "fall" if treated in the usual way by air-cooling. The following is a summary of the results of the tests carried out for this purpose.

Samples of foamed slag from different sources, when exposed to natural weather conditions on an open roof and when stored in sealed tins in the laboratory, have shown no change in 18 months, the duration of the test period to date. Storage of samples in water for periods up to six months has not caused breakdown or cracking. In comparison, unfoamed slags of similar composition (i.e. having a high lime content) have been observed frequently to crack and powder within 14 days from the time of immersion. Measurements of the change in volume of powdered samples have been made, using sensitive dilatometers constructed to allow of continuous observation over long periods. A small increase in volume has been observed in the majority of the samples; this takes place over the first few months and thereafter there is usually no further increase. The expansion is of the order of 0.02-0.03 per cent. The remainder of the samples showed no change during the observation period. Tests on concrete prisms using some of the samples as aggregate have shown that this small expansion has not caused any deleterious effects in the concrete during the six months period of examination. No cracking or breakdown of samples has been observed during annealing tests at various temperatures and for different periods of heating. Storage for periods of seven days in atmospheres containing steam at 100 deg. C. and oxygen has had no effect on any of the samples.

Some additional work has been carried out to devise tests suitable for ensuring that a batch of foamed slag is free from contamination by air-cooled slag or furnace coke. Tests for use in a standard specification for foamed slag aggregates have been communicated to the British Standards Institution.

Tests have been made to determine the effect on the strength of Portland cement concrete of adding finely-ground foamed slag, and the effect on the

strength of using foamed slag as a replacement for ordinary sand. Two types of slag were used, foamed slag and over-foamed slag (i.e. slag approaching the granulated condition). The investigation has shown that the finely-ground slag, whether of the foamed or over-foamed type, appears to have a cementitious value, when used in Portland cement concrete, practically equivalent to that of a similar quantity of cement (within the limit examined); also that the use of foamed slag in place of ordinary sand produces little change in the strength of Portland cement concrete, although a decrease in strength is produced when over-foamed slag is substituted. The loss in strength was practically regained, however, by adding finely ground slag, either foamed or over-foamed, although of the two batches used the foamed slag was preferable to the over-foamed slag.

The object of the investigation on air-cooled slags is to devise tests to determine the suitability for use in concrete of any sample of air-cooled slag. It is not yet possible to draw definite conclusions. Attention has been mainly concentrated on the study of the "falling" phenomenon, and it appears that the water immersion test may be promising as a method for determining stability. Volume changes have also been observed on "falling" slags by measurement in the dilatometers, while in some cases disintegration during annealing has taken place in slags selected at the blastfurnaces as likely to "fall." These tests, however, have been carried out on small spoon samples taken during the running of molten slag from the blast furnace. No attempt has been made as yet to apply them to the ordinary slags as used for concrete work. Some tests are also in progress on slag compositions prepared in the laboratory. It has been observed on these that immersion in alcohol or benzene is slightly more effective than water immersion in accelerating breakdown when this is likely to occur in normal open-air storage.

Limes and Plasters.

The only problem still outstanding in connection with the British Standard Specification for building limes is that of the method of testing hydraulic strength. After further investigation, it was decided that satisfactorily reproducible results would not be obtained without drastic modification of the method.

The feature of the old method most open to objection was the steaming at 100 deg. for two days ("stewing"). It was considered that the high vapour pressure of the water in the pores of the specimens must give rise to internal stresses, and that, although the specimens were previously hardened by drying, yet it might well be that strains were developed. Accordingly an investigation was undertaken of the effect of lowering the temperature of the water over which the specimens were placed. The results are given in Table 1 and Figs. 1 and 2. The coefficient of variation, which is given in the table, indicates that much greater uniformity is obtained when the vapour pressure is reduced. It is apparent that if the specimens are treated at between about 70 and 80 deg. C. for four days the strength developed is of the same order as that given by steaming at 100 deg. C. for two days and that over this range the effect of fluctuations in temperature of about 1 deg. C. or in time of heating of about one hour

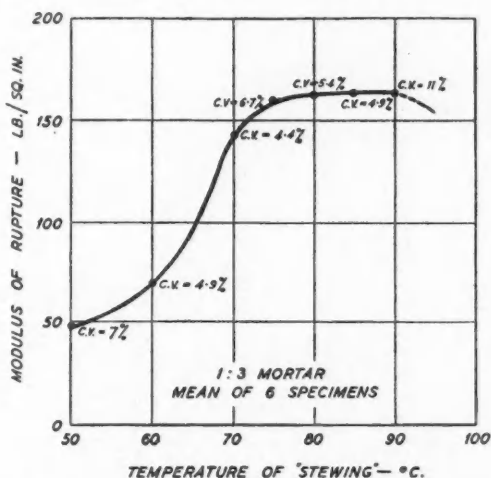


Fig. 1.—Effect of Curing Temperature upon the Modulus of Rupture of Lime Mortars.

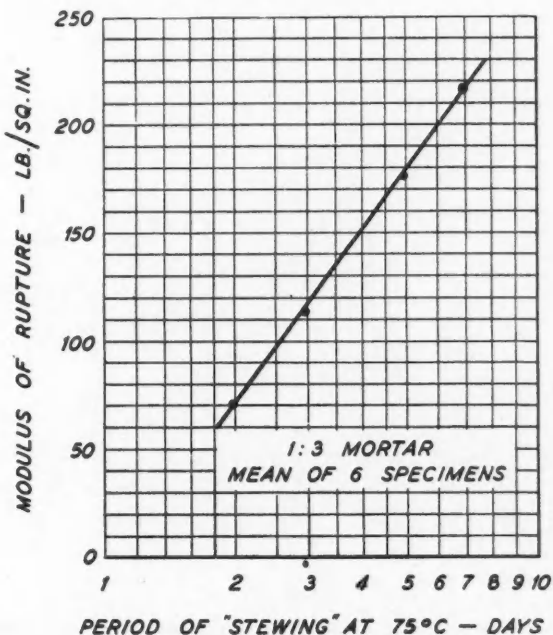


Fig. 2.—Effect of Time on the Modulus of Rupture of Lime Mortars cured at 75 deg. C.

TABLE 1.—EFFECT OF DIFFERENT ACCELERATED CURING TREATMENTS ON THE STRENGTH OF HYDRAULIC LIME.

Moderately hydraulic (greystone) hydrated lime. Mortar mix 1 : 3 by weight with standard sand. 66.2 per cent. water on lime throughout. Specimens tested wet.

Treatment.	Hydraulic strength. Modulus of rupture (lb. per sq. in.).	Coefficient of variation (%)
Dried at 37 deg. C. for 16-24 hours, then steamed for two days.	Mean of 132 specimens : 166 (Range 135-204)	On 132 specimens : 14.9% (Range on sets of 6 specimens : 3.3-26.8%).
Not dried. Cured in saturated water-vapour at 75 deg. C. for four days.	Sets of 6 specimens : 166 150 156 155 153 163* 161 162 Mean of 8 sets : 160	5.3 6.1 3.1 6.0 4.5 11.0* 4.7 4.5 Mean coefficient on all specimens : 6.7%

* One high result : 203 lb. per sq. in.

are not serious. Subject to confirmatory tests in other laboratories, early completion of the specification may therefore be expected.

Hydrated Limes.

Increasing interest is being manifested in the possibility of producing commercially a sound dry hydrated lime from the British Permian dolomitic or high magnesium limes. Such magnesian hydrates are commonly employed in other countries, especially in the United States; they are used even for plastering, where soundness is a more critical matter than in sanded mortars. But in the United States, as here, difficulties have been experienced in connection with a suitable soundness test. Whilst not suitable for magnesian limes, the soundness test developed at the Station for dry hydrated limes is satisfactory for all other limes.

Change of Title.—The title of the firm of Curt von Grueber Maschinenbau Aktiengesellschaft, of Teltow-Berlin, Germany, has been changed to Curt von Grueber Maschinenbauanstalt and the business is under the direction of Herr Ernst Curt Loesche.

Design and Operation of Modern Lime Works.—IX.*

By N. V. S. KNIBBS, D.Sc.

Miscellaneous Shaft Kilns.

Furnace-fired Kilns.—A furnace-fired kiln consists essentially of a vertical shaft with a furnace or furnaces attached a short distance above the drawing point. The hot gases from the fires pass under an arch through an opening in the kiln lining into the shaft and upwards. Furnace kilns have been used mainly in the United States and Canada and, although they are still used in large numbers there, they have little place in a consideration of modern efficient plant. The furnace kiln has evolved from the use of wood in lime burning, and if properly designed it is still a useful plant to employ in the few places where wood is now the cheapest fuel to use. Plants installed in recent years have sometimes included mechanical stoking arrangements and other labour-saving devices. These have improved the combustion and made heating more uniform, but have by no means justified this wrong principle of kiln firing.

The fundamental weakness of the furnace kiln lies in the fact that the heat is generated in the furnace and not amongst the lime, and consequently the maximum efficiency theoretically possible is low as previously shown¹. Furthermore heat losses through the furnace and kiln walls must be greater than in other kilns, and the heat in the lime is mainly or entirely lost owing to the air for combustion not passing to the furnace through the lime in the cooling zone.

To improve the performance of a furnace kiln it is obviously desirable to reduce to a minimum the air for combustion in the furnace and to draw secondary air up through the lime in the cooling zone to complete the combustion amongst the lime. When this procedure is carried as far as possible the gas-fired kiln with attached producers is the result, but there is an intermediate stage, the semi-gas-fired kiln, which will now be considered.

Semi-gas Kilns.—In the ordinary furnace kiln all the air used is drawn into the furnace, and in a producer-gas-fired kiln, using gas of the quality previously given², for each cubic foot of producer gas 0.68 cu. ft. of air is blown into the producer, and to burn it 1.37 cu. ft. of air are drawn up through the kiln, that is to say, an air ratio between producer and kiln of 1:2. In a semi-gas-producer kiln the distribution of air between semi-producer and kiln is intermediate, the ratio usually lying between 2:1 and 1:1.

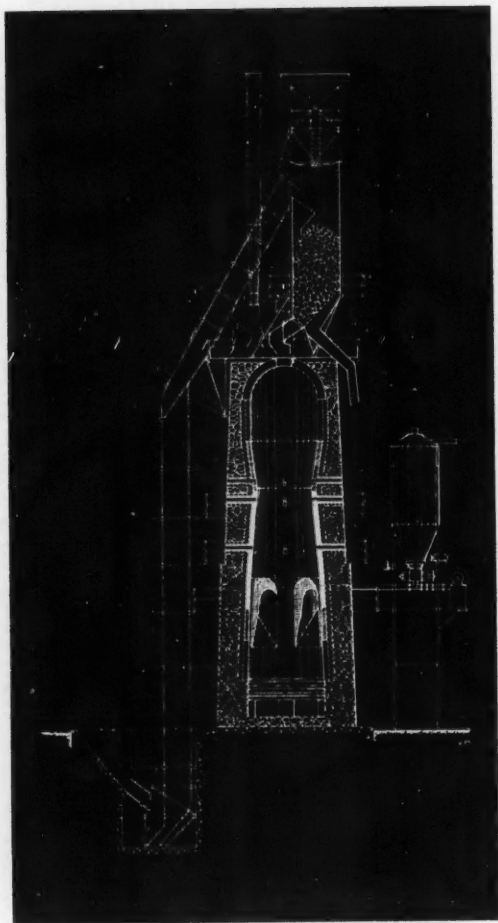
A semi-gas producer is simply a furnace with rather deep fire-bed and with some means of keeping the bed cool enough to avoid excessive clinkering. For example, water may be trickled down an inclined grate, or the fire bars may be

* Previous articles in this series appeared in our issues for January, February, March, April, May, August, September and October this year.

¹ *Cement and Lime Manufacture*, Jan., 1937, p. 7.

² *Cement and Lime Manufacture*, Sept., 1937, p. 240.

hollow and water passed through them, producing steam which is mixed with the air supply. They generally operate on natural draught under the suction of the kiln shaft, and are therefore well adapted to small isolated plants where mechanical complications are not desired. The design of the kiln shown in



(Dr. C. Otto, Bochum.)

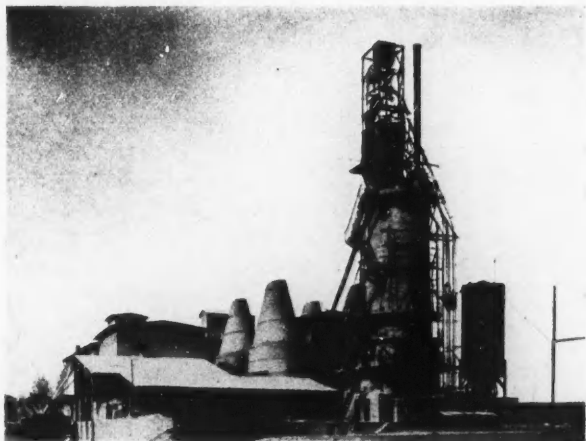
Fig. 38.—Coal-dust-fired Shaft Kiln.

Fig. 37^a is more like that of a semi-gas kiln than a full producer-gas kiln, and it would operate as a semi-gas kiln on anything but a highly reactive fuel.

^a *Cement and Lime Manufacture*, Oct., 1937, p. 285.

The Eldred Process.—In the Eldred process a proportion of the exhaust gases is mixed with the air passing under the furnace grate. It therefore cools the fire-bed by dilution, and also to some extent by the endothermic reaction of the carbon dioxide. Both effects tend to reduce clinkering of the fire, but the main benefit must be due to the supply of a larger volume of hot gases to the kiln, some of the heat of which is saved from loss in the furnace. The process is still in use, but it is no longer of interest where new plants are under consideration. It involves the use of an exhauster and is therefore inapplicable where power is not available—the only conditions under which this type of kiln is likely to be considered.

Oil-fired Shaft Kilns.—Oil firing was long ago applied to the ordinary furnace-fired kilns used in the United States, but the higher flame temperatures led to



(Dr. C. Otto, Bochum.)

Fig. 39.—Coal-dust-fired Shaft Kiln.

rapid destruction of the furnaces as constructed for other fuels, and it was necessary to modify them considerably. Modern oil-fired kilns have small combustion chambers where the oil is atomised and vaporised by a limited supply of air, the bulk of the combustion taking place amongst the lime. In this way the conditions of a gas-fired kiln are simulated as nearly as possible. Unfortunately central and intruded burners for oil are by no means easy to design, and oil-fired kilns generally have only side burners.

Coal-dust-fired Shaft Kilns.—Coal-dust firing as a means of lime burning has long been used in rotary lime kilns, but it is only recently that it has been applied to shaft kilns. Figs. 38 and 39 illustrate kilns fired in this way. The dimensions of the shaft are the same as those of gas-fired kilns built by the same makers, namely, in cross-section 7 ft. maximum width and a length depending on

the output required. It will be seen on comparing Fig. 38 with Fig. 34¹ that the opening in the kiln lining admitting the dust flame is much larger than the ports of the gas kiln. These openings serve as primary combustion chambers where the fuel is, in effect, gasified, the hot gas being burnt amongst the lime in the same way as gas in gas kilns. The air mixed with the coal (and serving to blow it into the kiln) and that admitted at the burner correspond to the air blown into the producer.

The advantages of coal-dust firing are economy of fuel and (as compared with manually-operated gas producers, but not with mechanical producers) less labour. The disadvantages are contamination of the lime and greater difficulty of control of the degree of calcination. Where a pure lime is not required it is likely that this system of firing will be more used in the future.

Static Kilns.

Flare Kilns.—All the shaft kilns previously considered are continuous in operation; that is to say, they are fed and discharged continuously or at intervals and remain continuously alight. Static kilns are lime-burning units which are filled with limestone, fired, cooled, and discharged, the lime remaining stationary in the kiln the whole time (except for any slight settlement) until it is discharged. Flare kilns, the oldest kilns of the type, are still in use. They are costly in labour and fuel, but when operated by experienced lime burners they make lime of good and uniform quality in large pieces, and it is mainly the fetish of the superiority of large lump lime that makes it possible to continue using them. The flare kiln consists essentially of a chamber with one or more grates at the bottom. An arch of large stone is built over each grate and the chamber is filled with stone, generally graded so that the small stone is at the top. A fire is lit on the grate and maintained until calcination is complete, when firing is stopped, the kiln is allowed to cool down, and is then ready for emptying.

In the original flare kiln all the fuel is burnt on the grate, and such kilns are still used with wood, for example in parts of Australia. With coal, however, unless the chambers are very small the heat will not travel through the whole of the stone without over-burning that nearest the fire, and consequently it is usual to add coal or coke to the stone when it is charged. This mixed fuel becomes ignited from the fire on the grate after the latter has been alight for some days. In other static kilns the fuel is all mixed with the stone but passages are left at the bottom (corresponding to the fire grate of the flare kiln) for admission of air and to light the kiln. Such kilns are in use in Sweden, burning lime with a low-grade oil shale, which is charged in layers between layers of limestone in large static chamber kilns.

Apart from the merit of making large lump lime almost free from small lime these chamber kilns have the advantage to the small producer of being convenient storages for the burnt lime. They are discharged as required to meet the demand, and the lime is loaded directly from the kiln on to lorry or rail wagon.

Ring Kilns.—The low thermal efficiency of a chamber kiln is due to the absence

¹ *Cement and Lime Manufacture*, Oct., 1937, p. 283.

of preheating of the air and stone in the lower part of the kiln and the waste of heat in the gases leaving at the top. Obviously to burn the stone at the top the gases must leave the kiln at 900 deg. C. or more towards the end of the burning period. To avoid these losses all that is necessary is to join three or more chamber kilns in series, the air or gases from the top of one passing to the bottom

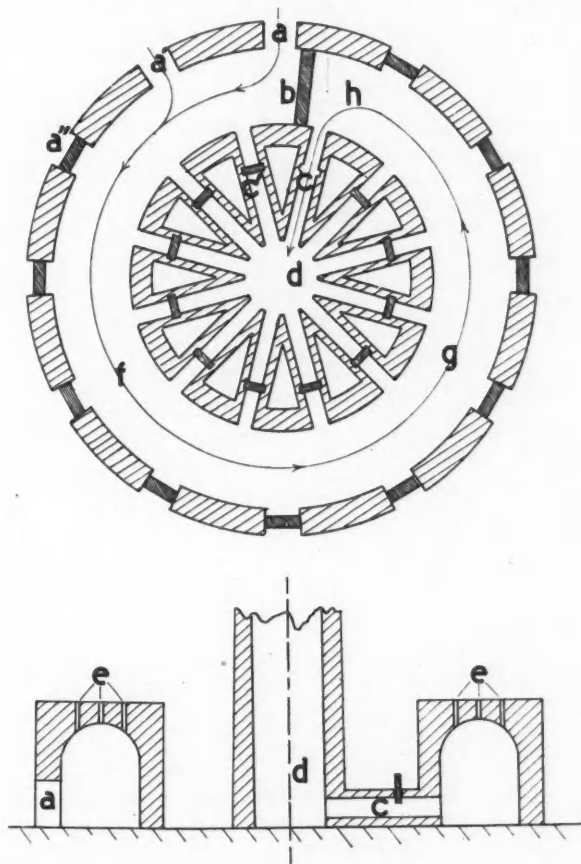


Fig. 40.

of the next, and so on. This is the principle of the ring or Hoffman kiln, and of various other horizontal kilns which are used mainly for burning bricks and other ceramic products, but which are also used to a considerable extent for lime burning. Although the ring kiln in principle is the same as a number of chambers joined in series, it is not necessary for the chambers to be separate, and the simple form of ring kiln employs one continuous chamber.

Fig. 40 is a diagrammatic representation of a simple ring kiln. The plan shows the interior of the kiln and represents a kiln with the upper half removed. It is also shown in vertical section, the left half being taken through the loading opening and the right half through the flue leading to the draught stack. The kiln consists of a circular chamber with arched top and openings *a*, *a'*, *a''*, etc., through which it is loaded and unloaded; *a* and *a'* are open but the remainder are bricked up. Limestone is wheeled in and stacked to fill the chamber completely. Air enters through *a* and *a'* and passes around the kiln in the direction indicated. Fuel is added through the openings *e* and burns throughout most of the burning zone *f-g*. From *g* to *h* is the preheating zone where the stone is heated up, the gases finally leaving the kiln through *c* to the stack *d*. A baffle *b* prevents air short-circuiting in the opposite direction. In the simple ring kiln *b* is made of paper and it is removed when required by tearing with a poker

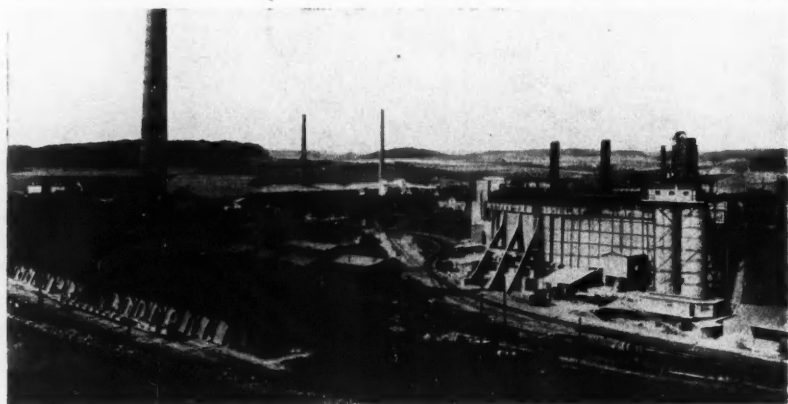


Fig. 41.—Ring and Shaft Kilns in Germany.

manipulated through an opening in the top of the arch. When the space between *b* and *a'* has been filled with stone and the lime removed between *a'* and *a''*, a new seal is placed near *a'*, *a* is bricked up, the damper *c'* is opened and *c* closed, and *b* is opened by tearing. The filling and emptying of one section generally takes one day, and at the same time the fire is advanced by a corresponding amount through gradually ceasing to feed at the holes nearest to *f* and starting to feed at the holes near *g*, that is to say, by advancing the feed holes. The fire thus advances continuously around the kiln, which operates in theory in the same manner as a shaft kiln.

Actually, ring kilns are never built in this shape. The more usual form consists of two parallel chambers joined at the end by semi-circular connections and with an exhaust-gas flue between the two and leading to a stack at the centre. This is the kind of kiln shown on the left in Fig. 41 and the same form is frequently employed for burning bricks. There are numerous variants, in

some of which the flue zig-zags around two sides of the square, but in principle they are all the same.

The weak point in this type of kiln is due to the contraction of lime which occurs when it is burnt, and which results in its subsidence in the tunnel, leaving a free space immediately below the arch through which the hot gases short-circuit. To reduce this tendency some kilns embody dropped arches spaced equally with the openings for charging, which to some extent reduce short-circuiting. Other ring kilns have distinct chambers with inlets and outlets near the bottom, which again reduce the tendency to short-circuit across the top. A further elaboration is to arrange flues under the floor so that each chamber is connected through openings in its base to the top of the next chamber. Fuel is spread over the top of the stone and the gases pass downwards through the chambers. These elaborations do not seem to have been commercially successful, and ring kilns for lime burning are generally of the simple type.

Another variant is to omit the top arch, that is to say, merely to have a long endless trough with side openings but no roof. The stone is filled into this trough and covered over either with bricks followed by fine ashes or other fine material, or by small limestone, and limestone dust. This type of kiln has the advantage that the covering sinks as the stone shrinks on burning so that there is no space left for short-circuiting the gases, but in other respects it is inferior to the enclosed ring kiln.

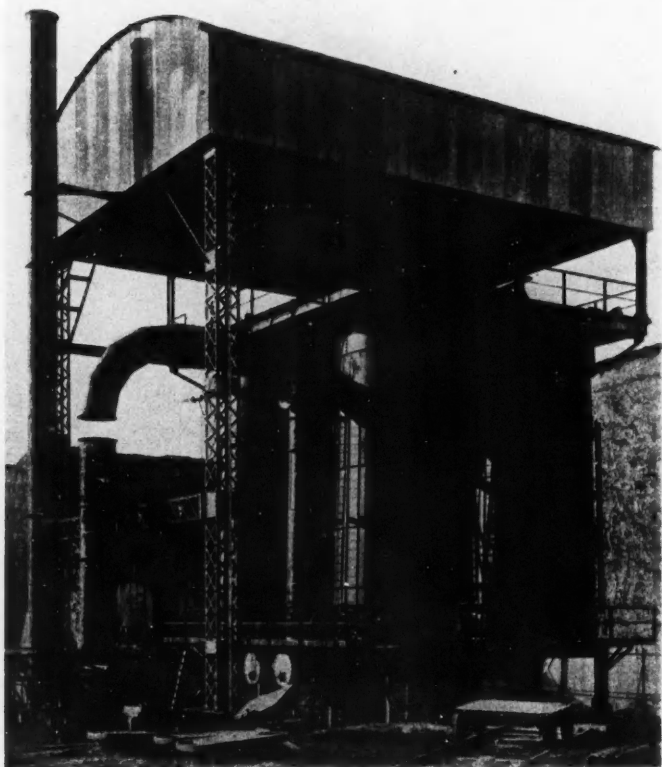
It has also been proposed to fill the space caused by contraction by adding stone through openings left in the arch, but this does not seem to have been a success. The openings must be so large and numerous as seriously to weaken the arch.

Ring kilns may be fired in several ways. The fuel may be uniformly mixed with the stone when it is charged, in which case only a non-volatile fuel should be used, otherwise the volatile matter is lost in the same way as from a mixed-feed kiln and one of the important advantages of the ring kiln is lost. Ordinarily, the fuel, generally bituminous coal, is fed into spaces left in the limestone through holes in the arch of each chamber and falls down cavities purposely left in the stone, lodging on projecting pieces and burning there. The fuel is charged when the kiln is ready to receive it, that is to say when the fuel added at the preceding holes is so far exhausted that the gases passing forward contain oxygen to burn the volatile matter liberated from the fuel charged. In other types of ring kilns fuel is charged into a separate compartment so that it does not come in contact with the lime, but this type is rarely used. Gas firing may also be employed, but unless a rich cold gas is available the complication and cost of providing flues with valves to each of the numerous chambers may make the kiln uneconomic.

The ring kiln is efficient in fuel consumption, and if it could be designed to be loaded and discharged mechanically it would also be economical in labour. There have been many attempts to design such a kiln, but without much success because the methods providing for loading and unloading always add enormously to the capital cost of the kiln and the added maintenance and running

costs are by no means negligible. The large area covered is often a disadvantage, and always adds to the cost of handling. The ring kiln to the left in Fig. 41, for example, has an area about the same as that of all the shaft kilns seen to the right, whilst the latter have an output many times that of the ring kiln.

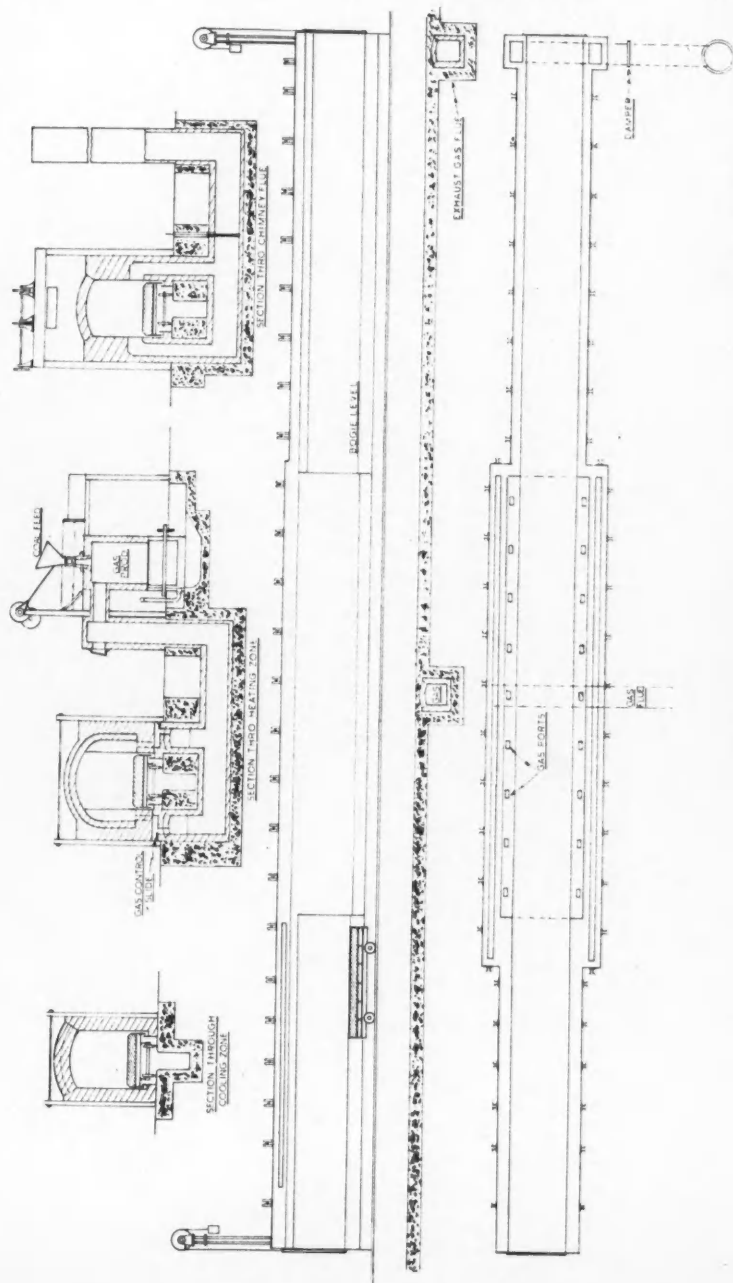
The outstanding merits of the ring kiln are its production of lime in large lumps with very little small lime, and the special quality of the lime made. It is burnt harder than shaft lime without being overburnt, due to its long period of heating at a moderate temperature, and in consequence the lime settles rapidly when used



(Messrs. Priest Furnaces, Ltd.)

Fig. 42.—Static Mix-Feed Kiln.

for water-softening, etc. Ring-kiln lime has commanded a higher price in the past than shaft lime, and this higher price, with the absence of smalls, has justified the higher cost of production. One would expect a ring kiln to be well suited to the production of chalk lime, and especially of greystone chalk lime, which, even to-day, is still burnt in flare kilns. It has been tried and its use discon-



(Messrs. Price Furnaces, Ltd.)

Fig. 43.—Tunnel Kiln.

tinued, but it is probable that the failure was due to poor design or supervision rather than to any failing inherent in the type of kiln.

Other Static Kilns.—There have been several attempts to combine the advantages of the chamber kiln with the thermal efficiency and ease of charging and discharging of the shaft kiln, using both the gas and the mixed-feed principles of firing. These attempts are mainly of historic interest because the illogical demand for lime in large lumps is gradually disappearing, and it is unlikely that anyone will in future install a kiln designed primarily to produce such large lime. One kiln of interest, designed for burning chalk, is shown in Fig. 42. It consists of four short shafts interconnected at the top and bottom through a system of flues and valves so that any three may be connected together in series and to the exhauster, the fourth shaft being out of series for emptying and filling. Provision is made for filling it through a hoist which runs down inside the shaft and tips automatically when it reaches the stone already charged, thus avoiding breakage of the chalk and damage to the lining. The kiln was designed to operate with coke mixed with the chalk.

A second kiln of some interest, designed to burn chalk in large lumps with gas, consisted of a number of refractory-lined chambers mounted on bogies and designed for coupling together and to the gas supply. Each acted as a down-draught chamber kiln, and their operation in series ensured a high thermal efficiency, whilst their mobility facilitated charging and discharging. The cost of a plant of this kind would obviously be high.

Tunnel Kilns.—The tunnel kiln which is used successfully for firing many ceramic products has been suggested for use in burning lime, and trials have been made with successful results. Nevertheless, this type of kiln does not seem to be actually in commercial use for the purpose. It is a continuous horizontal shaft kiln, the stone and lime being carried horizontally through the kiln on bogies in a direction opposite to that of the gases, and is, therefore, the same in principle as a vertical shaft kiln, but the stone and lime remain stationary in relation to the bogie and are not subject to abrasion, impact, etc. It has, therefore, the advantages of the static chamber kiln added to that of mobility of the bogies. As shown in Fig. 43, which represents a tunnel kiln not designed for lime-burning, but of the same type, the bogies are refractory-topped and cooled beneath by air, a sand seal separating the upper and lower tunnels.

The tunnel kiln is in many ways admirably suited to lime burning—with either gas or semi-gas firing. The combustion zone may be extended over any desired length and a fixed temperature maintained throughout this length within close limits, because of the simplicity of measuring and controlling temperature in the open space of the tunnel. By having a tunnel of sufficient length pre-heating and cooling may be effected completely, and by thorough lagging of the tunnel heat losses may be reduced to a minimum. A high thermal efficiency may in this way be combined with a low-burning temperature. The kiln also has the merit of producing all the lime in the form of lumps of any desired size.

(To be continued.)